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Acoustic Scaling

A one-eighth scale model reverberation room

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RESEARCH DEPARTMENT

ACOUSTIC SCALING: A ONE-EIGHTH SCALE MODEL REVERBERATION ROOM

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ACOUSTIC SCALING: A ONE-EIGHTH SCALE MODEL REVERBERATION ROOM

Summary

The development of a small-scale reverberation room is described and the factors which make it difficult to achieve a sufficiently high reverberation time are discussed. The report outlines the construction of the room (which was made principally from 13 mm thick steel plate) and its use in measuring the characteristics of model absorbers and absorbing materials.

1. Introduction

The work described in this report formed part of a study of the acoustics of music studios and concert halls by means of small-scale models. The essential characteristic of the materials to be used in such models is that their acoustical absorption coefficients should be the same as those of the materials used in the real studio but at k times the frequency, where 1/k is the scale-factor of the model; for the model of Studio 1, Maida Vale, the scale-factor is one-eighth.

Brebeck[1] measured the absorption coefficients of many materials for use in modelling and has produced data for about 90 arrangements of materials in the frequency range 1·25 kHz to 40 kHz. Useful though Brebeck's catalogue is, it does not give data appropriate for many of the materials actually used in the Maida Vale Studio.

Apparatus for the measurement of absorption coefficients in the range 400 to 80 kHz was not commercially available, and had to be designed first. The obvious approach was the construction of apparatus of conventional type, scaled dimensionally where appropriate.

One form of such apparatus consists of the impedance-tube, in which the standing-wave pattern in front of a layer of absorbent at the end of the tube is explored.[2] Although the method is speedy, absorption coefficients obtained in this way only apply for sound waves striking the absorbent at normal-incidence. The calculation of the random-incidence coefficient from the normal-incidence coefficient is lengthy, even for the restricted class of materials for which a conversion is possible. Impedance-tube measurements of absorption coefficients are generally made when an approximate assessment of absorption properties is required quickly. Because of the limited value of the measurements and the difficulties of scaling down the apparatus it was decided not to make a model impedance-tube.

The most important method for measuring random-incidence absorption coefficients employs a reverberation room. With this method, the reverberation time of a room having sound-reflecting walls, floor and ceiling is measured as a function of frequency before and after placing a known area of absorbent in the room. From measurements of reverberation time, taken with and without absorbent present, the absorption coefficient can be calculated using well-known formulae.[3] The method of measurement is specified in British Standard 3638:1963[4] which follows the recommendations of the International Organisation for Standardisation (ISO) very closely.

2. Requirements for a model reverberation room

Basically, a model reverberation room should conform to the standard requirements, scaled-down where appropriate. Table 1 shows the main requirements for a full-scale and one-eighth scale reverberation room.

TABLE 1

Requirements for Full-Scale and One-Eighth Scale Reverberation Rooms

Requirement	Full-Scale		One-Eighth Scale	
Recommended volume	200 m^3		0·39 m^3	
Minimum volume	180 m^3		0·35 m^3	
Area of absorber sample	10 m^2		0·156 m^2	
	R.T.(s)	f(Hz)	R.T.(s)	f(kHz)
Minimum reverberation times (R.T.) at stated frequencies	5·0	125	0·625	1
	5·0	250	0·625	2
	5·0	500	0·625	4
	4·5	1000	0·563	8
	3·5	2000	0·437	16
	2·0	4000	0·250	32

The volume of the room and area of the sample are specified because it has been observed that the results obtained in a full-size room depend on them. Minimum reverberation times are specified to ensure a marked fall in reverberation time after the introduction of a moderately-absorbent sample. The absorption coefficients of the surfaces of the empty room are kept small, so that the uncertainty of inclusion or omission of the absorption of that part of the room surface covered by the absorber sample is reduced.

In an empty full-size room, the absorption due to the air predominates at high frequencies; this limitation is reflected in the lower reverberation times specified above 500 Hz. The sound field in the room is required to be 'sufficiently diffuse' and British Standard 3638:1963 suggests that a number of diffusing plates be hung at random in the room, each plate having an area (single-side) of 0·8 to 2 m^2 so that their total area is approximately equal to the floor area. The sound insulation of the room should be sufficient to allow a signal-to-noise ratio of at least 40 dB.

3. Early attempts

The first attempts to model a reverberation room were not very successful. A model was made of metal-faced plywood, 13 mm thick but was rejected because its reverberation times were well below those given in Table 1. Poor bonding of the metal to the wood may have been the principal reason.

The second model was made with walls and floor of duralumin 6 mm thick, the internal surfaces being varnished in the belief that sealing the surfaces would reduce their absorption. The roof was made of clear acrylic sheet 13 mm thick, so that the microphone position in the chamber could be observed. Twenty-two diffusers of acrylic sheet, each 254 mm x 102 mm x 1·6 mm, were suspended at various angles from the roof. This model, although better than the first, still failed to reach the scaled-down ISO minimum reverberation times above 2 kHz, as is shown by curves (*a*) and (*d*) of Fig. 1. Ten diffusers were removed, but this increased only slightly the reverberation time above 2 kHz (curve (*b*)). It was then thought that the internal surfaces of the model were not sufficiently smooth and in view of the low absorption of acrylic sheet, the walls and floor of the chamber were lined with acrylic sheet 3·2 mm thick, bonded with a thin layer of impact adhesive. This proved to be disastrous, as is shown by curve (*c*). It seems likely that the damping of the adhesive layer was more serious than expected; later absorption measurements on laminated materials provided supporting evidence.

A search of the literature was then undertaken to see whether or not there was any fundamental limitation preventing the attainment of the required reverberation times.

4. Factors limiting the reverberation time

Absorption can be due either to air in the room or to the surfaces of the room. These causes are discussed briefly below, and in more detail in the appendix.

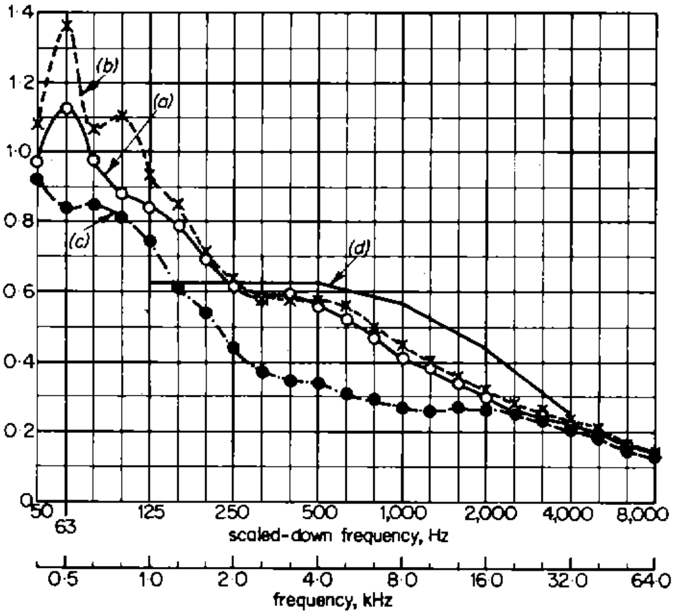

Fig. 1 - Reverberation time of model reverberation room Mk. II

(*a*) ○—○ Model reverberation room Mk. II with 22 diffusers, 2½% R.H. 20°C
(*b*) ×- - -× As (*a*) but with 12 diffusers only
(*c*) ●-·-● As (*b*) but after lining with acrylic sheet
(*d*) ——— Scaled down ISO minimum R.T. curve

4.1. Air absorption

The mechanisms by which air absorbs sound are discussed in many texts, e.g. Wood.[5]

First, the viscosity of the air results in sound absorption by the conversion of energy of motion into heat. The thermal conductivity of the air also gives rise to absorption by the flow of heat from the compressed regions of air to the rarefractions. Both of these mechanisms have been shown to give an amplitude attenuation coefficient which is proportional to the square of the frequency. For air, calculation shows that they would limit the reverberation time at 32 kHz to 1·1 s, considerably higher than the scaled-down ISO minimum of 0·25 s.

In damp air, absorption can also be caused by intermolecular energy exchange. In the water molecules translational molecular energy is converted into vibrational energy of the oxygen molecules; this absorption process is still a current topic of research.[6] The sound-intensity attenuation coefficient as a function of relative humidity (R.H.) and frequency is shown in Fig. 2, which is taken from Krauth.[7] At 32 kHz and 3% R.H., the molecular absorption limits the maximum reverberation time to 0·81 s; this effect, combined with the classical absorption, limits the reverberation time to 0·47 s, still considerably above the scaled-down ISO minimum of 0·25 s.

4.2. Boundary absorption

Any sound transmitted through the walls of a room is 'absorbed' so far as the reverberation processes inside the

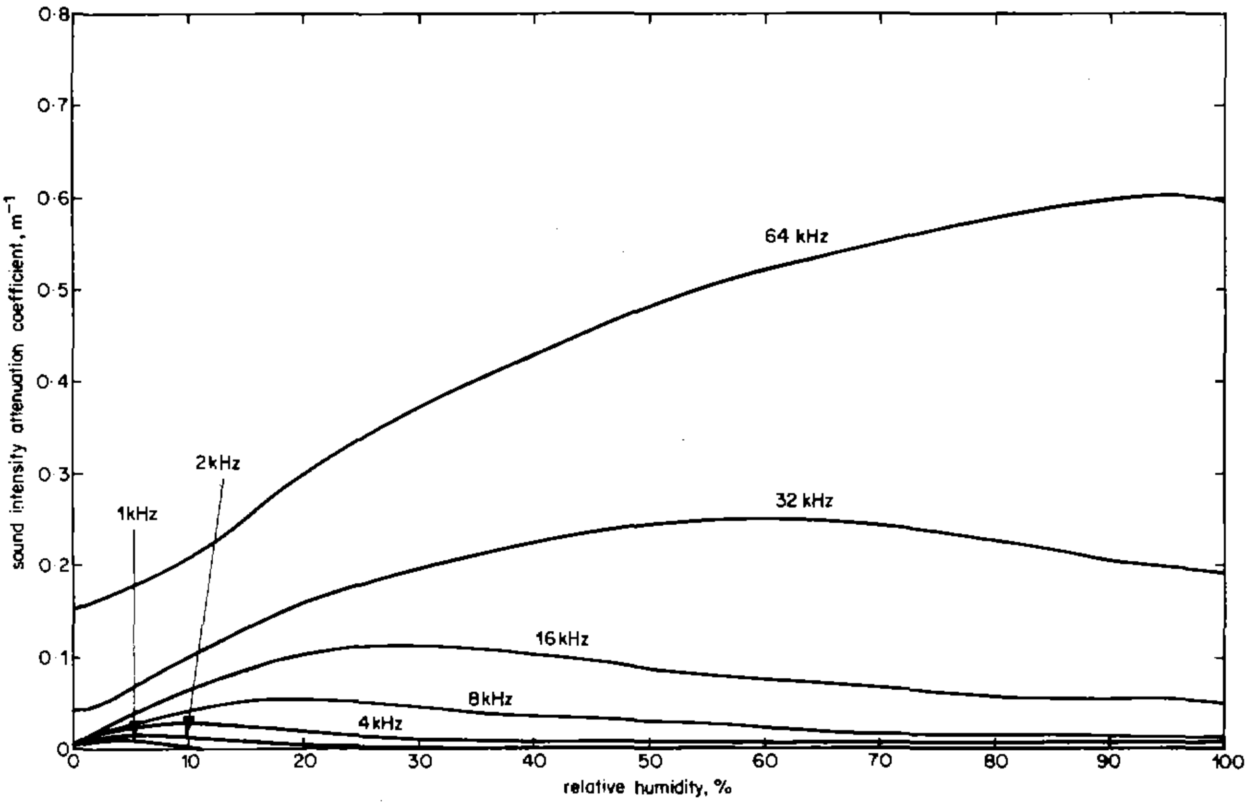

Fig. 2 - Dependence of sound-intensity attenuation coefficient on frequency and relative humidity (after Krauth[7]). The data from 1 to 8 kHz are based on measurements of Evans and Bazley[8] and from 16 kHz to 64 kHz on measurements by Pöhlmann[9]

room are concerned. In practice this need not be a limiting factor. In the mass-law region,* quite thin walls attenuate sufficiently. For example, walls of glass 5 mm thick, have a transmission loss greater than 20 dB above 400 Hz, corresponding to an apparent absorption coefficient of less than 0·01. The coincidence frequency (where there is an increase in the transmitted sound) can be brought below the frequency range of interest, if necessary, by increasing the wall thickness.

Even if the walls were perfectly rigid and smooth, absorption due to thermal and viscous losses in the boundary layer of air at the walls would still exist. This absorption mechanism was discussed quantitatively by Cremer in 1948, and more recently by Walther.[10] This 'unavoidable' absorption coefficient is proportional to the square root of the frequency. In a one-eighth scale reverberation room it alone limits the reverberation time to 0·63 s at 32 kHz.

4.3. Minimum absorption

In a model reverberation room having the scaled-down volume of 0·39 m^3 recommended by the ISO and an internal surface area of 3·22 m^2, the absorption mechanisms discussed above result in the total absorption** at 32 kHz shown in Table 2.

TABLE 2

Minimum Attainable Absorption at 32 kHz and 3% R.H. in Model Reverberation Room

Absorption Mechanism	Absorption (m^2)
Classical absorption	$5{\cdot}8 \times 10^{-2}$
Molecular absorption	$7{\cdot}8 \times 10^{-2}$
Unavoidable surface absorption	$1{\cdot}0 \times 10^{-1}$
Total absorption	$2{\cdot}4 \times 10^{-1}$

This restricts the maximum reverberation time at 32 kHz and 3% R.H. to 0·27 s, only just above the 0·25 s required.

It was clearly necessary to minimise wall losses as far as possible.

5. Mark III reverberation room

The Mark III model reverberation room was made with the walls and floor of steel plate, 13 mm thick, welded together. The worst irregularities in the internal surfaces were removed with abrasives, but no attempt was made to fill or polish the surfaces. Because it was necessary to *observe the position of the microphone and in order to gain* access to the inside of the model, the acrylic sheet roof of the earlier model was used, together with the suspended acrylic sheet diffusers. The volume of the model was 0·388 m^3 and the surface area 3·22 m^2.

* The region where the effects of stiffness on the transmission loss of a wall may be neglected.

** Absorption here means the area of perfect absorber having the same absorbing power as the mechanism under consideration.

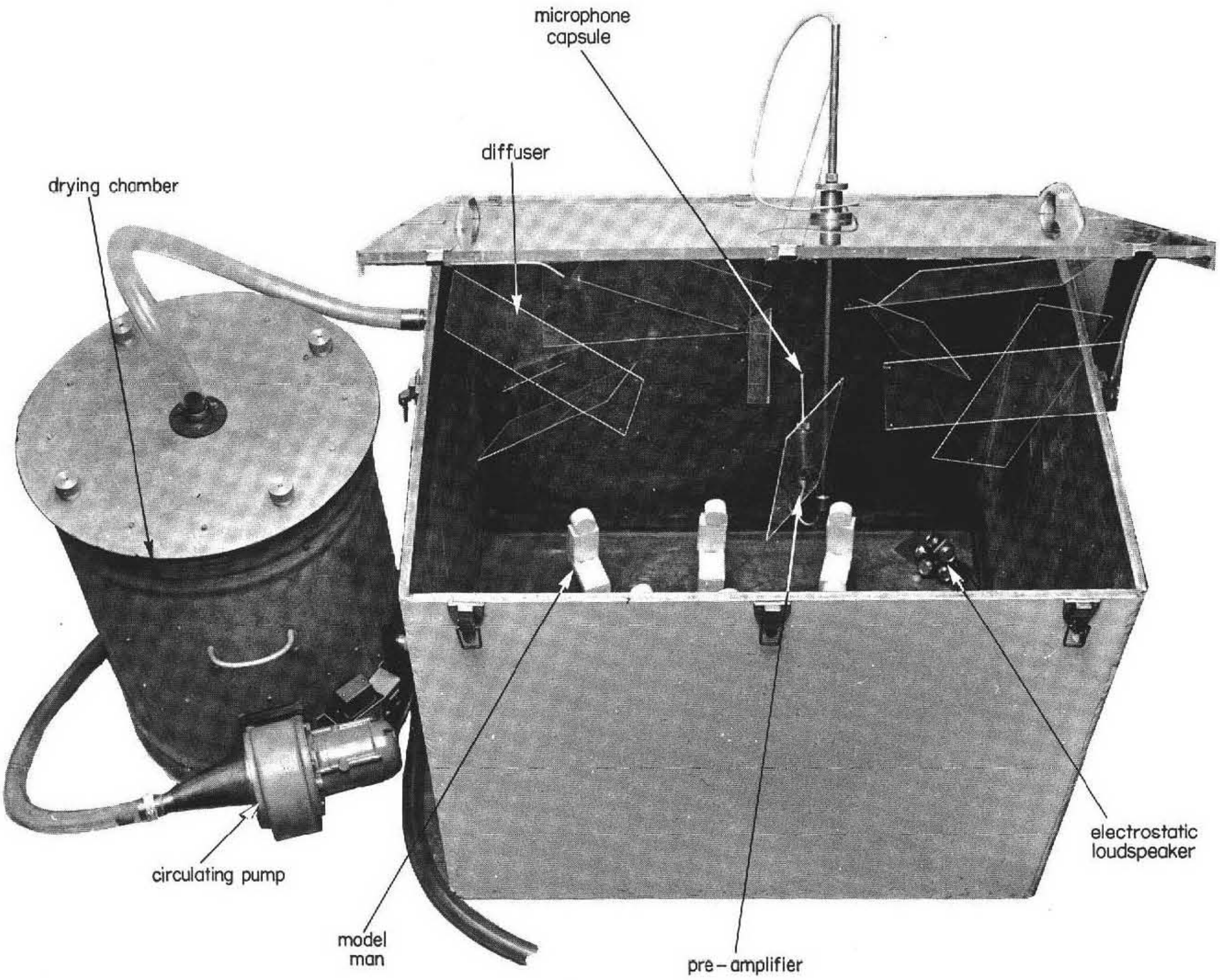

Fig. 3 - Model reverberation room Mark III with drying apparatus (roof shown raised)

Fig. 3 shows the reverberation room and the associated drying apparatus, a drum containing synthetic zeolite pellets through which air is pumped from and to the room. The reverberation-time/frequency curve of the room with a relative humidity of less than 1% is shown by curve (*a*) in Fig. 4. The ISO minima (curve (*c*)) are exceeded at all points. The published data on the sound absorption of air at relative humidities around 1% does not appear to come from many independent sources and so, as a check, the reverberation room was filled with nitrogen, a gas whose absorption is wholly attributable to classical mechanisms in the frequency range 4 kHz to 100 kHz. The resulting reverberation-time/frequency curve is shown as curve (*b*) of Fig. 4. The similarity between curves (*a*) and (*b*) shows that absorption due to intermolecular energy exchange has been largely eliminated.

The wall absorption was then calculated by, first, subtracting the classical absorption and molecular absorption for air at an R.H. of 1% from the total absorption of the air-filled chamber and, second, subtracting the classical absorption of nitrogen from the absorption of the nitrogen-filled chamber. The mean surface absorption coefficients derived from these calculations are shown in Fig. 5., curves (*a*) and (*b*). The good agreement indicates that the published absorption data for air around 1% R.H. is sufficiently accurate. For comparison, the values of 'unavoidable' absorption calculated from Cremer's formula (see appendix) are shown, curve (*c*).

6. Measurements on absorbers

6.1. Technique

For measurements of reverberation time, the room was equipped with a ¼-inch diameter capacitor microphone, on a boom, whose position could be adjusted from outside the room. A specially-developed low-noise pre-amplifier replaced the manufacturer's capsule amplifier. Test signals were emitted by a conventional moving-coil tweeter in the range 400 Hz to 10 kHz and, for the range 10 kHz to 80 kHz, an array of five 25 mm diameter electrostatic loudspeakers were used. Details of these and other parts of the instrumentation involved in the model technique will be given in a later report in this series.

Because of early difficulties associated with a multi-speed tape recorder nearly all the absorption measurements were made using the oscilloscope-display method of reverberation time measurement; this was adapted for the higher frequencies by modifying parts of the apparatus. The excitation signal was provided by a wide-band noise generator, the output of which was passed through a set of one-third octave filters. The output of the microphone amplifier was fed to the same set of filters, then to a wide-band logarithmic amplifier and then to the oscilloscope.

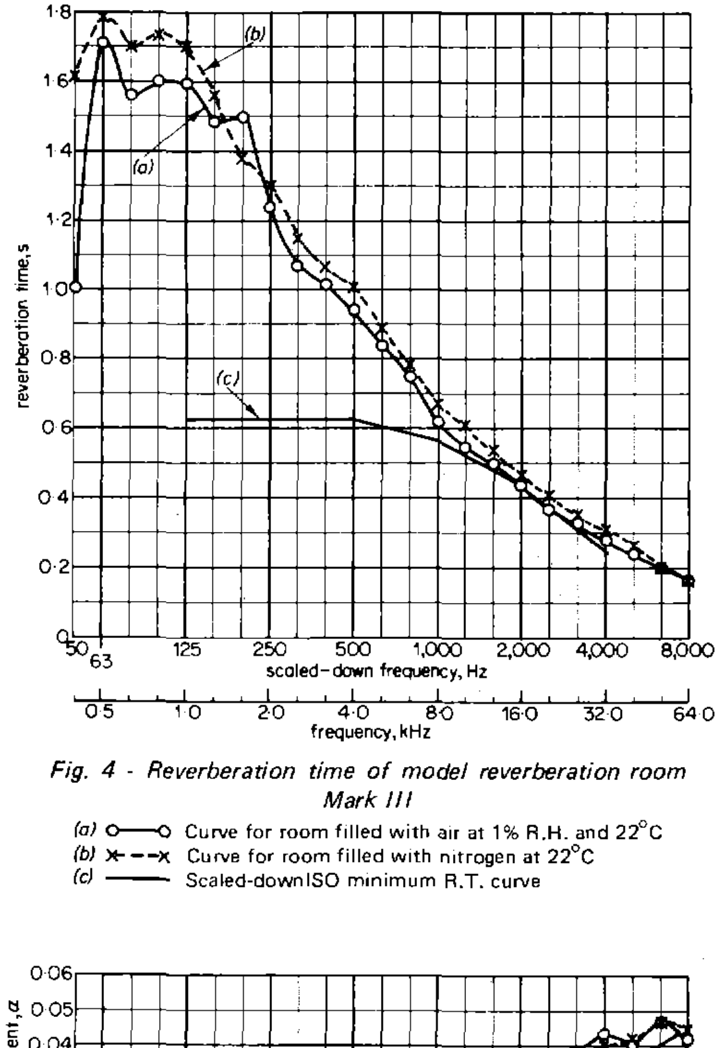

Fig. 4 - Reverberation time of model reverberation room Mark III

(a) o——o Curve for room filled with air at 1% R.H. and 22°C
(b) x- - -x Curve for room filled with nitrogen at 22°C
(c) ——— Scaled-down ISO minimum R.T. curve

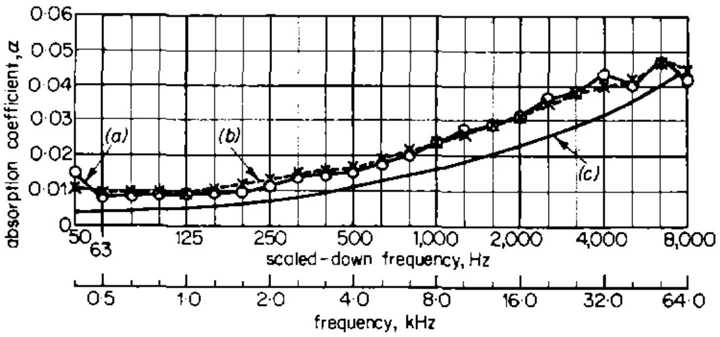

Fig. 5 - Mean absorption coefficient of surfaces of model reverberation room Mark III

(a) o——o Calculated using data on absorption of air at 1% R.H.
(b) x- - -x Calculated using data for the absorption of nitrogen
(c) ——— 'Unavoidable' absorption from Cremer's formula

After the problems with the multi-speed recorder had been solved, measurements were made using a modification of the automatic method of measurement developed for testing remote studios.[11] The normal test-tape permits up to 3½ s of decay curve to be recorded at audio frequencies, which is ample for most purposes, but inadequate for measurements in a full-size 200 m^3 reverberation room. A special test-tape was therefore prepared having test signals and intervals of twice the normal duration. This was played at eight times the normal speed into the model reverberation room and the microphone output recorded simultaneously. The new recording was then replayed into the automatic processing equipment at *one-quarter* the speed at which it was recorded, thus producing signals having the normal time intervals. The computed reverberation times were then doubled. This method was very rapid, and removed the uncertainties arising from changes in humidity occurring during a lengthy measurement by the oscilloscope method.

The most frustrating aspect of the measurements was the long time (sometimes a matter of days) before most of the moisture was extracted from an absorber sample. This was alleviated to some extent by pre-drying samples in a separate chamber whenever possible.

6.2. Configuration of absorber samples

Most of the absorber samples were prepared in accordance with scaled-down ISO recommendations; i.e. samples were single, of approximate area 0·16 m^2, and the edges were lined with reflecting surfaces.

Some types of practical absorber are distributed in studios in relatively small patches rather than in large unbroken areas. When measuring models of such absorbers in the model reverberation room they were divided into four samples of equal area, one on the floor and three on the walls. It was found convenient to attach small permanent magnets to the back of the samples so that they could be held to the walls easily.

6.3. Accuracy of measurements

Calculations show that at frequencies above 2 kHz an error of 1% R.H. in the region around 2% R.H. would generally give an error of 0·05 in the absorption coefficient of the sample; errors of ± 1% R.H. seem likely to occur. No attempt was made to control the temperature of the room during measurements and this can be a considerable source of error at the highest frequencies, because the classical absorption of air varies with temperature. At 100 kHz, an 'empty' room measurement at 18°C and a 'with sample' measurement at 23°C would result in an error of 0·1 in the computed absorption coefficient. Fortunately, because the classical absorption is proportional to the square of the frequency, the errors below 30 kHz are negligible.

Errors in absorption coefficient arising from errors in reverberation time measurement are difficult to assess. At frequencies below 1 kHz, the wavelength is becoming comparable with the dimensions of the model reverberation room and there is no basis upon which errors can be calculated. Above 1 kHz the standard error of the mean of a set of reverberation time measurements is generally of the order of 3% and this corresponds to an error in absorption coefficient of less than 0·05 if the reverberation time is greater than 0·24 s. Above 32 kHz where the reverberation time is necessarily less than 0·24 s the error can rise to approximately 0·10. These errors could be almost doubled if the errors in the empty room measurements happen to be in the opposite sense to those of the measurements made with the sample present. On the other hand, if the errors in the empty room measurements have the same sense as the errors with the sample present, they tend to cancel out.

Provided care is taken to avoid large temperature differences and to dry the room and sample well, it is reasonable to expect errors in absorption coefficient to be about ±0·05 for frequencies between 1 kHz and 32 kHz and ±0·10 outside this frequency range. Similar errors are obtained in a 200 m^3 room at audio-frequencies.

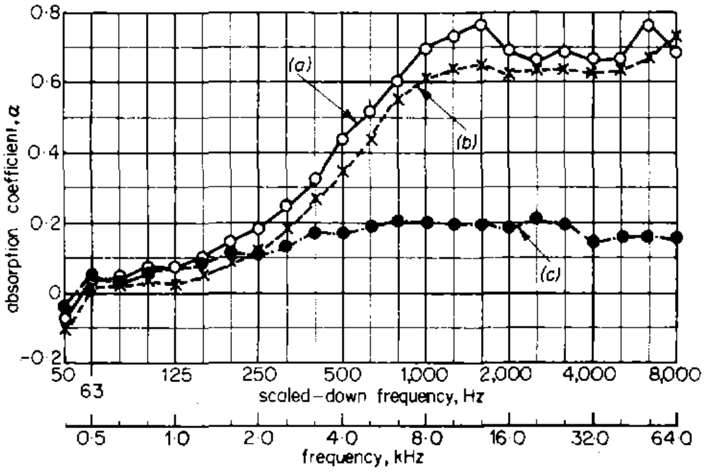

Fig. 6 - Examples of results for absorbers

(a) ○——○ Green velvet, superficial density, 0·46 kg/m^2
(b) ×- - -× Gold velvet, superficial density, 0·42 kg/m^2
(c) ●-·-● Green flock sprayed on to 19 mm blockboard

6.4. Examples of results for absorbers

Fig. 6 shows examples of results for three absorbers. A negative absorption coefficient often appeared at 400 Hz and is undoubtedly a manifestation of the failure of the reverberation time formulae at wavelengths comparable with the room dimensions. Similar negative coefficients have been encountered in a full-scale reverberation room at low frequencies.

7. Further applications

The ease with which conditions can be changed in a model reverberation room opens up new possibilities in the testing and examination of certain theories in room acoustics, which would otherwise be too difficult or expensive to carry out at full-scale. Investigations into the best shapes for diffusers and reverberation rooms come into this category.

8. Conclusions

A one-eighth scale model of an ISO standard reverberation room has been successfully built from steel plate 13 mm thick. It has scaled-up reverberation times exceeding the minima recommended by the ISO. If reasonable care is exercised in controlling the humidity of the air in the model, the errors in absorption coefficient are similar to those occurring in the use of a full-scale reverberation room.

The room could be used as a means of testing certain theories about room acoustics and absorbers more cheaply and more quickly than in a full-size room, as well as for testing absorbers for scale-model studios.

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APPENDIX

1. Air absorption

The absorption arising from viscosity and thermal conduction (classical absorption) was derived theoretically by Stokes and Kirchhoff but experiments have since shown a value of energy absorption about 50% higher than is given by theory. The measured classical energy absorption coefficient is given by[1]

$$m_c = (33 + 0{\cdot}2\,T) \times 10^{-12} f^2\,(\mathrm{m}^{-1}) \qquad (1)$$

where T is the temperature in °C

f is the frequency (Hz)

The energy absorption coefficient per unit length arising from intermolecular energy exchange is given by:

$$m_m = \frac{2\mu_{max} f_{max}}{c(1 + (f_{max}/f)^2)} \qquad (2)$$

where $\mu_{max} = RC_i/C_v(C_v - R)$

c = Velocity of sound in air

R = Gas constant

C_v = Specific heat of air at constant volume

C_i = Internal specific heat of the oxygen molecules

and f_{max} is the frequency at which the molecular absorption is at a maximum.

Monk[6] gives the following empirical value for f_{max}:

$$f_{max} = 1{\cdot}305\,h'^{1{\cdot}45} \qquad (3)$$

$$\text{for } 1 < h' < 10$$

where h' is the mole fraction of water vapour times 10^3.

From Equation (2) it can be seen that the value of m_m at $f = f_{max}$ is proportional to f_{max}.

2. Boundary absorption

The 'unavoidable' absorption coefficient at a perfectly smooth and rigid boundary is given by:[1]

$$\alpha_{unv} = 1{\cdot}8 \times 10^{-4} f^{1/2} \qquad (4)$$

f is the frequency (Hz)

Walther[10] derives the general expression leading to this formula. The principal assumptions are that the sound energy density is distributed uniformly and that at the wall isothermal conditions exist as opposed to adiabatic conditions elsewhere.

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